# XPLANE, a Generative Computer Aided Process Planning System for Part Manufacturing

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SUMMARY:

This paper reports on the development of XPLANE, a generative computer aided process planning system for part manufacturing. Described is its position and functioning as a part of a more extended computer aided manufacturing system that includes a link to CAD systems, as well as systems for computer aided design and selection of jigs and fixtures, NC part-program generation, tool management and capacity planning. The XPLANE system automatically selects tools, machining operations and their sequence starting from a full part description created by a boundary-representation solid modeller. Apart from the description of the CAM environment the paper focuses on some of the most important specifications of XPLANE, the knowledge driven expert system, i.e. the knowledge representation, the inference engine, the explain facility and the knowledge-base editor.

## 1. INTRODUCTION.

Although the flexibility offered by modern CNC machine tools on its own is reasonably high, when placed within a manufacturing system or a manufacturing cell the flexibility is limited, amongst others, by the number of direct accessible tools and NC-programs. The amount and the complexity of the data required for the generation of both error-less and cheap NC-programs is very large and justifies the research and development for automatic information processing in this area. Up to now separate developments have resulted in a number of more or less on its own existing NC programming systems that execute the selection of cutting conditions and the determination of cutting paths. However, some of the most important bottle-necks in the integration of computer aided manufacturing systems are the design and selection of jigs and fixtures, the selection of tools and the selection and sequencing of machining operations (process and operations planning), which up to now has been the exclusive domain of experienced human planners. GENERATIVE process planning will increasingly become a necessity where fixturing design, tool selection, process and operations planning and capacity planning (scheduling) are coming together in a sense that they have to be carried out simultaneously and within a limited period of time. This being caused by the single presence of the different types of machinetools, limited availability of tools and such prevailing factors as small batch sizes and short throughput times. What is needed are integrated CAM systems with a high degree of automatic decision-making and information processing but, by reason of the required flexibility, with extensive possibilities of interactive use. One of the major problems of the existing systems is their incapability to adapt to changing conditions (e.g. various machine tools, different materials, tools and machining operations). They are based on current or sometimes even obsolete knowledge and are only capable of retrieving old solutions. Although the logic and expert knowledge applied in process and operations planning etc. is by no means simple to represent in a computer system, both the disadvantages of the "storage and retrieval" systems and the necessity of integration of Computer Aided Design and computer aided manufacturing systems call for the development of generative Computer Aided Process Planning systems. First the paper concentrates on the description of the concept of a largely integrated planning system and subsequently focuses on one of the main systems called XPLANE, a process and operations planning expert system.

## 2. AN INTEGRATED CAD/CAM SYSTEM CONCEPT.

An efficient and reliable use of CAD/CAM systems must come from the integration of product design, planning, scheduling and management functions together with a frequent re-use of implemented data. Our present design concept of an integrated CAD/CAM system includes a number of different systems, each of them having his own specific function:

1) A boundary-representation solid-modeller (see 2.1),
2) A system for computer aided design and selection of jigs and fixtures FIXES (see 2.2),
3) The XPLANE process planning system (see 4),
4) A module for NC part-program generation (see 2.3),
5) A tool-management module (see 2.3),
6) A cell-capacity planning module (see 2.3).

The different systems use a common data-base to facilitate information transfer from one to another. A future prototype implementation will incorporate both a common user environment and multiwindow (multi-screen) facilities to enable the operator to run different modules simultaneously. Paragraph 3 supplies an example describing the way in which the operator can interact with such an integrated system. Figure 1 shows the present state of the implementation. Figure 2 visualizes the whole design concept.

### 2.1 The boundary-representation solid-modeller.

The integrated system comprises a boundary representation solid-modeller. It is used to supply both the part- and blank product-descriptions. A product description must be complete. It must contain all relevant information needed by the other system members. Therefore the solid-modeller specifications include:

1) a mathematically exact geometry representation (and not a faceted one) to be able to distinguish between e.g. a plane and a cylindrical surface,
2) a possibility to store additional, non geometrical, data e.g. material specifications and surface-roughness data,
3) a facility to specify dimensions, position and shape tolerances of the product.

The solid-modeller being used in our case is based on the G.P.M. solid-modeller, which is being developed as an Inter Nordic project (1), (2). The G.P.M. modeller has been made available to us by the Department of Manufacturing Systems of the Royal Institute of Technology in Stockholm. This modeller is one of the very few modellers available that meet the required specifications. The integrated system however is not restricted to the use of the G.P.M. modeller since it is connected to the remainder part of the system via a well defined interface. The interface enables replacement of the G.P.M. modeller by a different boundary representation solid-modeller that meets the specifications mentioned earlier.

### 2.2 The computer aided design and selection of jigs and fixtures system FIXES.

FIXES is a technology based fixture-design expert-system that is also developed in our laboratory. For a given workpiece the system will be able
- to determine the (number of) fixtures necessary,
- to select necessary positioning, clamping and supporting aids for every fixture,
- to synthesize these aids into fixtures,
- to deliver the data for the construction of the fixtures.

All the data relevant to FIXES will be collected from the common data-base. A link between FIXES and the common data-base is nearly completed. Up to now the FIXES system has retrieved its information from a plain 2D technical drawing. A limited prototype-version of FIXES has been delivered to industry in 1985. However an agreement on confidentiality prohibits the publishing of any detailed report for yet another year.

### 2.3 The other systems.

Apart from the solid-modeller, FIXES and XPLANE, non of the other systems mentioned in paragraph 2 are actually implemented. The tool-management module and the capacity-planning module only exist in concept. However, in the past few years much work has been directed towards the development of CAPP systems like ROUND (3) and CUBIC (4) which incorporate extensive parts of the functions required. ROUND is a working prototype for turning. CUBIC deals with box-type products and has been developed at earlier date. Its implementation has been stopped for future adaptation to the XPLANE system. The NC part-programming module will be taken from CUBIC.

## 3. THE OPERATOR - SYSTEM INTERACTION.

In common-day practice a planner is simultaneously engaged in the design of fixtures, the determination of machining methods and machining sequences and the selection of tools So, separate systems are required to support the planner in each of the specific tasks. These systems have to be integrated in an overall planning system. Working with such a system will incorporate continuous switching between the "modules" to achieve a multi-way work-preparation process adapted to today's practice. It is expected that this switching process can be handled by the program in most cases, i.e. without interference of the operator. However a direct intervention facility has to be made available to the operator along with an explain facility which offers the opportunity to trace-back the system's decisions. The operator experiences the integrated system as just one large computer program that is capable of performing a number of specific tasks. The operator - system interaction is the same for every part of the system, since all modules use the common user-environment. Information exchange between the different systems is maintained by a single common data-base in which all data related to products, machines, jigs and fixtures, materials and tools as well as generated NC-programs etc is stored. Figure 3 shows a possible operator-system interaction-process.

1) A product model is created by using a combination of sweep- and boolean operations with additional user primitive operations supported by the G.P.M. solid modeller. Furthermore material specifications, surface-roughness data and tolerances can be specified. Product models, as well as partial products, can be stored in, or retrieved from, the common data-base at any time; also for design and engineering purposes.

2) The cell capacity planning system can be used to pre-select a machine tool and a toolset.

3) The fixture-design expert-system (FIXES) is used to design and select the required jigs and fixtures based on the specifications of a selected machine tool available tools and practical machining operations.

4) The XPLANE system subsequently selects adequate machining operations and tools for the machining of the product based on the previously selected toolset, machine tool and fixture.

    The procedures under 3) and 4) have to be carried out at least once for every selected fixturing position!!

    If the XPLANE system is not capable of selecting a satisfactorily set of machining operations and tools due to restrictions imposed by the fixturing solution, the operator can consider alternative fixtures by re-running the fixture expert system.

    If the XPLANE system is not capable of selecting a satisfactorily set of machining operations and tools due to restrictions imposed by the pre-selected toolset, the operator can select a different toolset by re-running the capacity planning system and re-running XPLANE.

    In both cases it may be necessary to consult the tool-management module with respect to the availability of tools, jigs etc.

5) The NC part-program generation system calculates the cutting conditions and the cutting paths, based on data supplied by the previous programs and stored in the common data-base. This system also estimates machining times and costs, which data are used in relation to machine tool selection and capacity planning.

    If the NC part-program generation system fails to determine satisfactory cutting conditions, the operator may re-run the XPLANE system after supplying a different toolset.

6) The cell-capacity planning system schedules the operations based on the previously calculated times. The scheduled occupation of the selected machine tool, toolset etc. is confirmed.

    At choice the operator may re-run the NC part-program generation system and prescribe alternative cutting conditions and thus generating new costs and time estimates in order to avoid bottle-necks in the capacity planning of a manufacturing cell.

The integrated system is structured in such a way that the most obvious alternative solutions can be found by re-running only the previous system. However nothing will prevent a re-run of any of the other systems if required. But it would for instance not be very practical to select alternative fixtures in order to solve bottle-necks in the cell-capacity planning. This strategy is aimed at selecting an overall and adequate solution allowing an increased degree of optimisation in each successive step and this being achieved within a limited amount of time and with a minimum of (cpu-time) costs. Figure 4 and 5 illustrate the mechanism behind the strategy.

In figure 4 the FIXES module is not able to find a satisfactorily solution. After re-running the previous module (cell-capacity planning module) and selecting an alternative solution, the FIXES system will be able to find a satisfactorily solution as shown in figure 5.

## 4. XPLANE, DESCRIPTION OF THE SYSTEM.

XPLANE stands for eXpert process PLANning Environment. The system contains a number of modules (see figure 6) which will be discussed in the next paragraphs (5). The decision-making related to both machining operations and required tools is based on initial unstructured knowledge, stored in a readable and easy to understand knowledge-base. Using the knowledge-base driven expert system approach, XPLANE is not only capable of generating adequate process plans but the system is also capable of evaluating a number of alternative solutions and of selecting an optimum solution from them. The evaluation is carried out based on a generalized cost-equation. By using the explain facility of the system, an experienced user can obtain advise concerning a possible modification and re-structuring of the knowledge in the knowledge-base. This approach offers a number of advantageous features in comparison with the "storage and retrieval" systems:

1) the possibility to implement company specific machining methods in the knowledge-base,
2) the possibility to frequently evaluate and modify the decision criteria based on information obtained in manufacturing practice, in order to install knowledge related to better manufacturing methods,
3) the possibility to maintain and develop company specific know-how in a practical way,
4) the possibility to be used by - and as a training tool for - less experienced personnel.

One of the most important aspects of a knowledge-base driven expert-system approach undoubtedly is the fact that it enables experienced planners to specify, maintain and improve the knowledge in the knowledge-base. Such a system can significantly improve the accessibility of a company's know-how. It can furthermore be considered as a basis for standardization of both machining methods and tools.

### 4.1 The feature recognition module.

XPLANE requires a full product-description of both the blank and the ready-part. It is the function of the "feature recognition" module to examine the product model, stored in the common data-base and to detect any feature (e.g. a hole, a slot or a pocket) that needs to be machined. Features are characterized by shape definition, geometrical and technical data. The feature recognition module is based on an algorithmic approach borrowed from Choi, Barash and Anderson (6). Paragraph 5, table 1 shows an example of the hole-feature parameters used by XPLANE.

### 4.2 The knowledge-base.

The XPLANE knowledge-base contains two different kinds of information:

1) FACTS, related to the available machine tools and tools (e.g. the diameters of the drills available for a given machine tool).
2) RULES, (e.g. IF a hole with a "flat bottom" surface has to be machined THEN you can use an end-mill for the final operation).

The issue of knowledge representation mainly depends on the knowledge domain (7). Since the human expert's knowledge tends to be fragmented and unstructured, so called production rules have been adopted for the representation of this knowledge. A production rule consists basically of two parts:

1) a number of conditions,
2) a number of actions.

IF condition(s) THEN action(s).

The action resulting from a rule can be applied if the conditions stated in that rule are met. An example of such a rule, with an additional APPLICATION keyword to indicate a particular kind of feature for which the rule can be used, is given below:

```
APPLICATION hole
IF          hole_surface_roughness   LARGER_THAN    5.
    AND     hole_bottom_type         NOT_EQUAL_TO   flat_bottom
    AND     thread_type              EQUALS         not_present
THEN
    CALL DRILLING ( hole_diameter, hole_length )
ENDIF
```

The knowledge-base including all interrelations between different rules and corresponding conditions and actions is stored explicitly in the common data-base.

### 4.3 The inference engine.

Different from a conventional algorithmic system, domain specific decision rules are stored in the knowledge-base, which is external to the expert system. By consulting the knowledge-base, the expert system is capable to infer decisions based on these rules. This part of the system is usually called the inference engine. The consultation mechanism is based on the substitution of feature parameter values in the production rules. The XPLANE system uses a backwards search method (8) that starts with a completely machined part feature and searches for "inverse operations" that fill up the feature until it blank state is achieved (see figure 7).

#### 4.3.1 The graph search method.

The inference mechanism is based on a graph search method (7). Starting with a completely machined part feature (a so called more-worked-feature) a number of action-parts of different rules from the knowledge-base can be applied (since all conditions stated in those rules are met); each of them suggesting a different (inverse) machining operation. This results in the generation of a corresponding number of so called less-worked features.

If none of the newly generated less-worked features is equal to the un-machined feature (blank) every one of them is suitable to become a more-worked feature during the following step. In this way a "tree-shaped decision-structure" develops. An extra pruning mechanism is added to the inference engine to guide the search process. By estimating the machining costs (see 4.3.2) for every generated set of machining operations, and after comparing the different cost-values with each other, the inference engine continues search with the most promising (say less expensive to machine) of the less-worked features available. Figure 8 shows an example of the decision tree generated for the hole-feature shown in figure 7. The expert system approach offers the possibility to generate a number of alternative machining operations by continuing the search after a successful set of machining operations has been detected.

#### 4.3.2 The cost-equation.

The design of a cost-equation is a significant matter with respect to the selective functioning of the search method. The cost-equation used is of the shape:

$$f(n) = g(n) + h(n)$$

where $f(n)$ = the value of the cost-equation for node n in the tree,
$g(n)$ = an estimation of the cost associated with the machining operation(s) selected to reach node n,
$h(n)$ = an estimation of the cost required to reach an end-node (the un-machined feature) starting from the present node n.

In the current pre-prototype implementation of the cost-equation g(n) is simply associated with the number of operations necessary to reach node n (this value does not yet depend on the operation types necessary to reach node n) and h(n) is associated to the remaining percentage of the material that still needs machining. More detailed equations will be developed in the near future.

### 4.4. The knowledge-base editor.

The knowledge-base editor has to guide the operator when modifying the production rules. The editor offers facilities to:

1) change an existing rule,
2) add a new rule to the knowledge-base,
3) re-activate a previously deleted rule,
4) search in the knowledge-base for the occurrence of facts, conditions, actions or parts of them.

In the near future research effort will be directed to the implementation of an automatic deficiency and consistency checking module.

### 4.5 The explain facility.

Because the decisions are based on explicitly defined rules, a knowledge-base driven expert system is able to explain it's line of reasoning. XPLANE stores all relevant information for possible consultation afterwards during which the system can tell exactly why a given machining operation has been selected. The explain facility offers the following facilities:

1) It can visualize the generated decision-tree structure for each part feature of a product, and highlight the selected set of machining operations and tools.
2) It can visualize both the feature parameter values and the associated value of the cost-equation for every node in the decision tree.
3) It can display the source-text of any consulted rule and show the evaluated results either for the entire rule or for each of the separate conditions.

The explain facility is of great help during the knowledge acquisition and the implementation phase of the expert system. It will also prove to be a very useful tool for the training of less experienced planners.

## 5. A PROCESS PLANNING EXAMPLE.

A wire-frame drawing of the product is presented in figure 9. The common data-base contains a real solid model of this product and a number of surface roughness specifications and tolerances which have not been made visible in the wire-frame drawing.

The feature recognition module of XPLANE has scanned the product description in the common data-base and has detected one single hole-feature. The extracted feature parameter values are listed below:

The inference engine has selected a set of machining operations and corresponding tools based on the product specifications, the pre-selected machine tool and the pre-selected toolset. The decision-tree structure generated is presented in figure 8. The selected set of machining operations and the tools are listed in table 2 in the sequence of machining.

The operator examines the system's line of reasoning by using the explain facility. The interactive interrogation is fully menu-driven. Examples are given in tables 3 and 4.

FEATURE hole:

| | |
|---|---|
| to be removed volume | 6280. |
| hole diameter | 10. |
| hole length | 20. |
| hole bottom type | flat bottom |
| diameter previous operation | not present |
| previous operation | not present |
| boring operation present | no |
| hole completely finished | no |
| chamfer angle | 45. |
| length of chamfer | 2. |
| thread type | not present |
| length of thread | not present |
| pitch of thread | not present |
| nr of threads per revolution | not present |
| nr of threads per inch | not present |
| nr of hole-parts left | 0. |
| surf roughness top-face | 20. |
| position tolerance | .5 |
| hole surface roughness | 16. |

Table 1, Hole feature parameter-values.

| Machining operation | Tool diameter |
|---|---|
| 1. Drilling | 8 mm. |
| 2. Milling | 10 mm. |
| 3. Chamfering. | -- |

Table 2, Selected machining operations.

SHOW THE RULE CONSULTATION RESULTS FOR NODE 1:

All pre-conditions are satisfied for rules 9 and 12.

One or more of the pre-conditions are not satisfied for all the other rules.

SHOW THE CONDITION CONSULTATION RESULTS FOR RULE 8 AND NODE 1:

```
APPLICATION hole
IF      hole surface roughness >=  5.           <true>
  AND hole bottom type         <>  flat bottom  <false>
  AND thread type              =   not present  <true>
THEN
        CALL DRILLING ( hole diameter, hole length )
ENDIF
```

Table 4, Rule consultation example.

The present implementation of the explain facility supports only rather basic facilities. It is essential that additional functions are added to this module (e.g. facilitating english responses instead of 'true' and 'false') so that it can be used as a training tool for less experienced planners. The explain facility is very useful during the knowledge acquisition and implementation phase. Modifications to the knowledge-base can be made by using the system's knowledge-base editor.

## 6. CONCLUSIONS.

The introduction of automatic information processing systems (like NC-part programming systems) in part manufacturing, especially in flexible manufacturing systems for small batch sizes, has emphasized the crucial importance of process- and operations planning. The design and selection of fixtures and the generation of new process plans has become a bottle-neck. The introduction of computer aided process -and operation planning systems that assist human planners and use expert knowledge, can solve this bottle-neck if these systems can be integrated with the existing CAD/CAM systems. XPLANE is such an expert process planning system. The present XPLANE implementation detects hole-features from a product model created by a boundary-representation solid-modeller, and selects the required machining operations and tools. The prototype is implemented in standard FORTRAN-77 on a micro VAX

II. Present developments are directed towards the implementation of additional product features like slots and pockets in both the feature recognition module and the knowledge-base. Although no direct effort is made in that direction, it is believed that the approach can also be applied for the selection of machining operations and tools in turning. Further efforts will be directed to the design and implementation of a more selective cost-equation and additional functions in both the knowledge-base editor and the explain facility.

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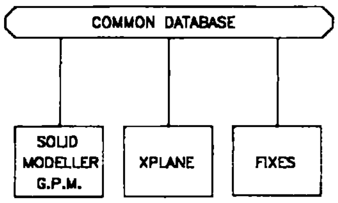


FIGURE 1. THE PRESENT STATE OF IMPLEMENTATION.

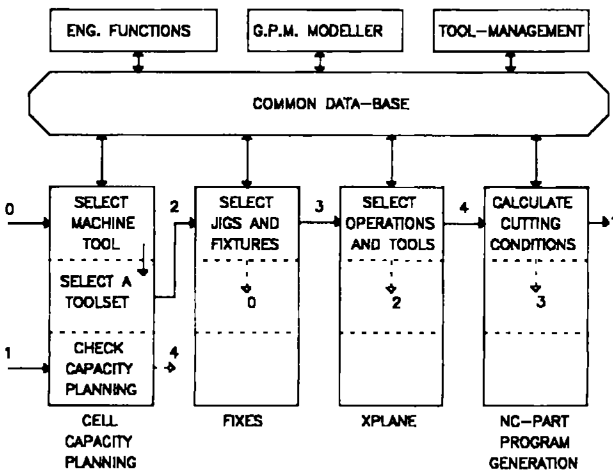


FIGURE 3. EXAMPLE OF OPERATOR-SYSTEM INTERACTION-PROCESS.

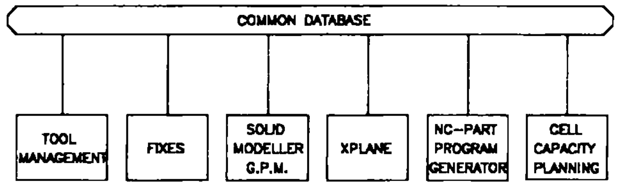


FIGURE 2. THE ENTIRE CONCEPT.

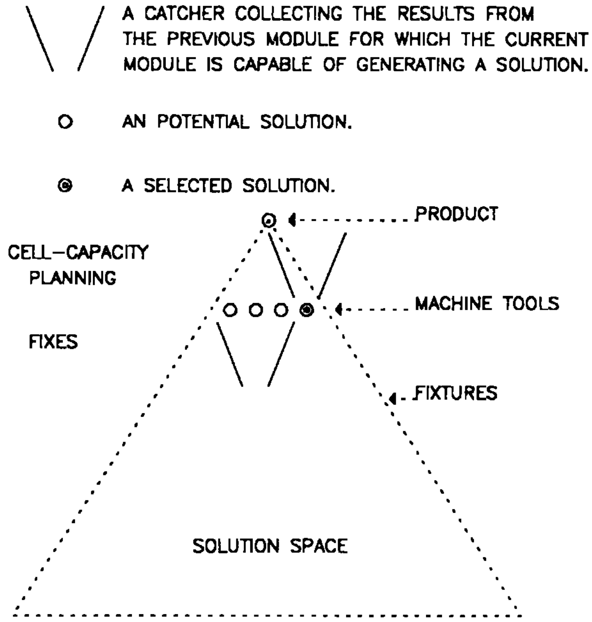


FIGURE 4. EXAMPLE OF A NON SUCCESSFUL RUN.

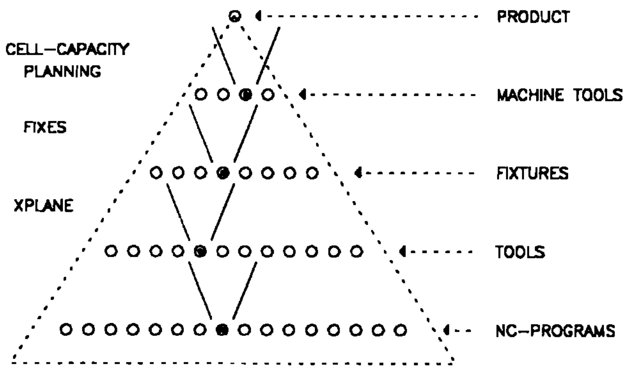


FIGURE 5. EXAMPLE OF A SUCCESSFUL RUN.

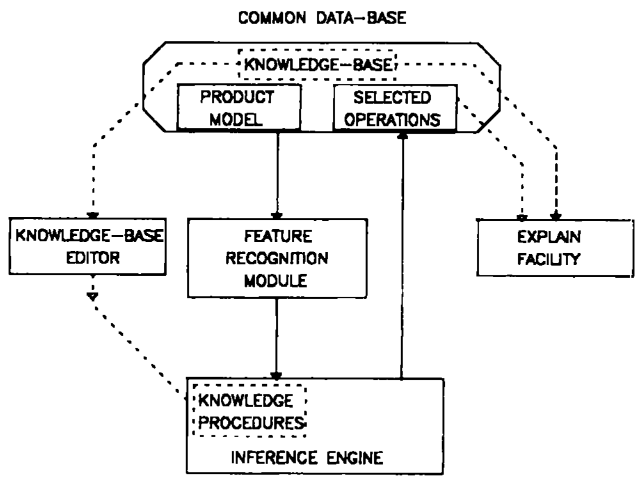


FIGURE 6. EXPERT PROCESS PLANNING ENVIRONMENT.

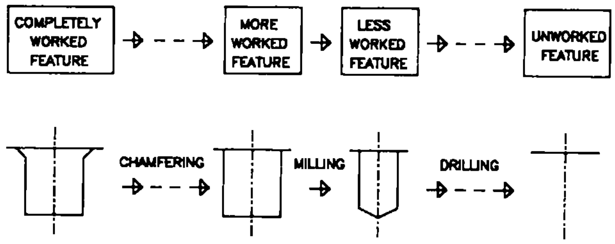


FIGURE 7. BACKWARDS SEARCHING.

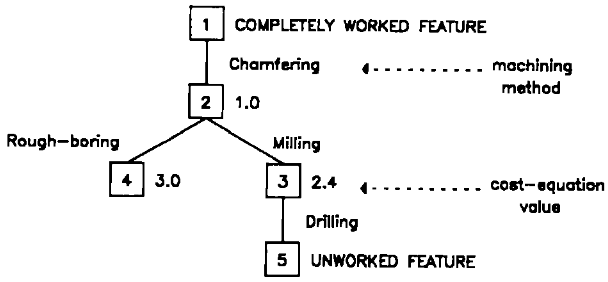


FIGURE 8. DECISION-TREE STRUCTURE.

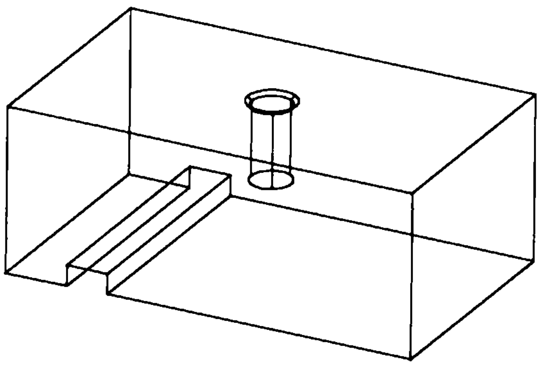

FIGURE 9. WIRE-FRAME REPRESENTATION OF A PRODUCT MODEL.